



**COLLABORATIVE
SOLUTIONS TO
MITIGATING
CONTRAILS WITHIN
AIR TRAFFIC
MANAGEMENT**

**SHAPING
OUR
FUTURE
SKIES**

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Contents

ACKNOWLEDGEMENTS	3
EXECUTIVE SUMMARY	4
1. INTRODUCTION	5
2. PURPOSE AND SCOPE	6
3. CURRENT STATE OF CONTRAIL SCIENCE AND ATM OPERATIONS	7
3.1 Factors Influencing Contrail Formation	8
3.2 Contribution of Flights to Contrail Formation	9
3.3 Climate Metrics and Impact Assessments	10
3.4 Scientific Uncertainty	10
4. CURRENT MITIGATION INITIATIVE AND OPPORTUNITIES	11
4.1 Policy Initiatives	11
4.2 Early-stage Operational Trials	11
4.3 High-impact Mitigation Opportunities	12
4.4 Effects of Engine Design and Fuel Composition	12
5. FUTURE CONTRAIL MITIGATION ROLE FOR ATM	13
5.1 Collaboration and Roles	14
5.2 ATM Considerations	16
5.3 ATM's Role in a Hybrid Contrail Mitigation Approach	18
6. CHALLENGES	24
6.1 Technical Challenges	24
6.2 Operational Challenges	24
6.3 Regulatory Challenges	25
6.4 Implementation Challenges	26
7. CONCLUSION	27
REFERENCES	28

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Executive Summary

Contrails, or condensation trails, are artificial clouds formed by aircraft at high altitudes that can persist for hours in the atmosphere. The phenomenon originates from the difference in temperature and humidity between the exhaust gases emitted by the airplane's engine and the surrounding air. This causes water vapor to condense and freeze into ice crystals that both scatter incoming sunlight back to space and trap the Earth's outgoing thermal radiation.

Though often transient in appearance, their contribution to climate change via the greenhouse effect from persistent cirrus cloud formation is potentially significant. With increasing awareness of aviation non-carbon dioxide (non-CO₂) impacts, contrails have emerged as a key focus in aviation's environmental strategy. It is estimated that less than three percent of global flights caused 80 percent of the contrail warming in 2019; therefore, mitigating the impact of a relatively small number of flights may significantly reduce global contrail impacts.

Scientific research is ongoing to understand, predict, quantify, and mitigate the impacts of persistent contrails. Solutions can potentially include implementation of aircraft technologies and alternative fuels that will reduce the non-CO₂ effects, as well as operational management when viable to avoid the formation of persistent contrails. Operational management can consist of flight level changes, flight trajectory planning, and/or real-time alternate routing. Implementation of any solution demands a collaborative effort among Air Navigation Service Providers (ANSPs), airlines, regulators, aerospace manufacturers, meteorological services, and researchers. While regulatory frameworks evolve, efforts must emphasise operational feasibility, economic sustainability, and scientific rigor.

Operational management of contrails requires integrating contrail mitigation techniques within Air Traffic Management (ATM) without compromising safety. Mitigation strategies must also consider potential impacts on operational efficiency for all Airspace Users (AUs).

Historically, many operational contrail mitigation efforts have focused on airline-led flight planning and operational trials. While valuable, these demonstrations lack scalability and system-wide coordination. Contrail mitigation should be framed as a shared challenge in which ATM plays a central, enabling role. The next step in research and development should focus on harmonised strategies, informed trade-offs, and synchronised action to integrate environmental priorities within global ATM systems.

Contrail mitigation presents a near-term opportunity to reduce a potentially significant part of aviation's climate impact. Given that only a small fraction of flights is responsible for the majority of contrail-induced warming, targeted mitigation—such as rerouting flights to avoid persistent contrail formation regions—has the potential to yield meaningful climate benefits without requiring large-scale changes to the entire air traffic system.

The paper highlights that effective contrail mitigation will require collaborative action among airlines, air navigation service providers, regulators, and meteorological services, supported by improved forecasting, operational tools, and evolving regulatory frameworks. Efforts to integrate contrail mitigation strategies into air traffic management must be coordinated, data-driven, and balanced with operational efficiency and safety.

1. Introduction

As the aviation industry works to reduce its carbon dioxide (CO₂) impact on the environment, aiming to achieve net zero by 2050, growing attention is being placed on the climate impact of non-CO₂ effects, particularly those caused by contrails.

Contrails, short for condensation trails, are cloud-like formations. These trails are composed of ice crystals that can evolve into persistent cirrus clouds, trapping outgoing longwave radiation, and thus contributing to atmospheric warming. Though less persistent than CO₂, contrails, particularly those forming in Ice Supersaturated Regions (ISSRs), can have a comparable or greater near-term climate forcing effect. While carbon dioxide emissions have long been the focus of climate mitigation efforts due to their longevity in the atmosphere, the short-lived but potent warming effects of contrails are now receiving increased attention.

Emerging scientific results suggest that contrails may have a near-term climate impact equivalent to or greater than that of CO₂, despite their comparatively brief lifespan. [1][2][3] This insight has positioned contrail mitigation as a strategic opportunity—an achievable, low-cost mitigation within the broader context of sustainable aviation.¹

Contrail mitigation presents a near-term opportunity to reduce a portion of aviation's climate impact. Deep decarbonisation efforts will require large investment and long timeframes to implement, whereas contrail mitigation may be possible at lower costs in the near to mid-term.

AUs can play a role in contrail mitigation in several ways, including using different fuels or engines. ANSPs may also support contrail mitigation by enabling operational contrail avoidance strategies. A more effective outcome may be achieved when both parties align their respective approaches to support contrail mitigation collaboratively. Operational contrail mitigation may be possible through the avoidance of ISSRs, and specifically high-impact areas which are referred to in this paper as Contrail Mitigation Target Regions (COMTARs).

CANSO recognises that the aviation sector is pursuing mechanisms to reduce the formation and persistence of warming contrails to manage the climate impact of aviation. This requires an integrated strategy that combines improved contrail science and prediction capabilities with the development and introduction of technical and operational solutions as well as a clear legal framework.

¹ Teoh, Roger, et al. "Global aviation contrail climate effects from 2019 to 2021." *Atmospheric Chemistry and Physics* 24.10 (2024): 6071-6093.

2. Purpose and Scope

This paper explores the current state of science and mitigation strategies surrounding contrail formation, with emphasis on potential strategies for multi-stakeholder, collaborative ATM approaches. The operational, economic, and regulatory challenges as well as the climate impact of proposed strategies will be discussed.

This paper introduces the key stakeholders involved and outlines the main drivers behind the need for a shared mitigation approach. These drivers provide a foundation that enables proposed strategies and solutions to be assessed within a collaborative framework. Any potential contrail mitigation strategies should be tested by this reasoning to explain how this approach can benefit all stakeholders.

AUs and ANSPs each have potential approaches to reduce contrail impacts, most notably through navigational avoidance. The avoidance of contrails with high potential impacts is achieved by avoiding particularly persistent contrail areas, described in this paper as COMTARs. The locations of these target regions can vary as weather and atmospheric conditions change over time – they are not simply fixed locations in the atmosphere.

Recognition of COMTARs will help to focus mitigation efforts on high-value targets rather than considering individual aircraft in isolation. A COMTAR is defined as a region with three main characteristics:

- The region is atmospherically prone to generate persistent warming contrails (accounting both for the location and its temporal aspect);
- A significant number of aircraft may be generating contrails in the region, and
- Stakeholders have agreed to coordinate contrail mitigation in the region (assuming policies are in place to encourage such coordination).

Finally, this paper proposes potential solutions and strategies starting from a collaborative approach but with a focus on the role of air traffic management. The challenges related to these potential strategies will be described based on the total climate impact, economic viability, and operational viability. This will generate a first step towards defining a shared ANSP approach in line with other aviation stakeholders for the coming years.



3. Current State of Contrail Science and ATM Operations

In the context of ATM, several factors are important to understand contrail formation and mitigation, including the likelihood of occurrence, seasonal variability, geographical distribution, and the typical altitude and extent of ISSRs.

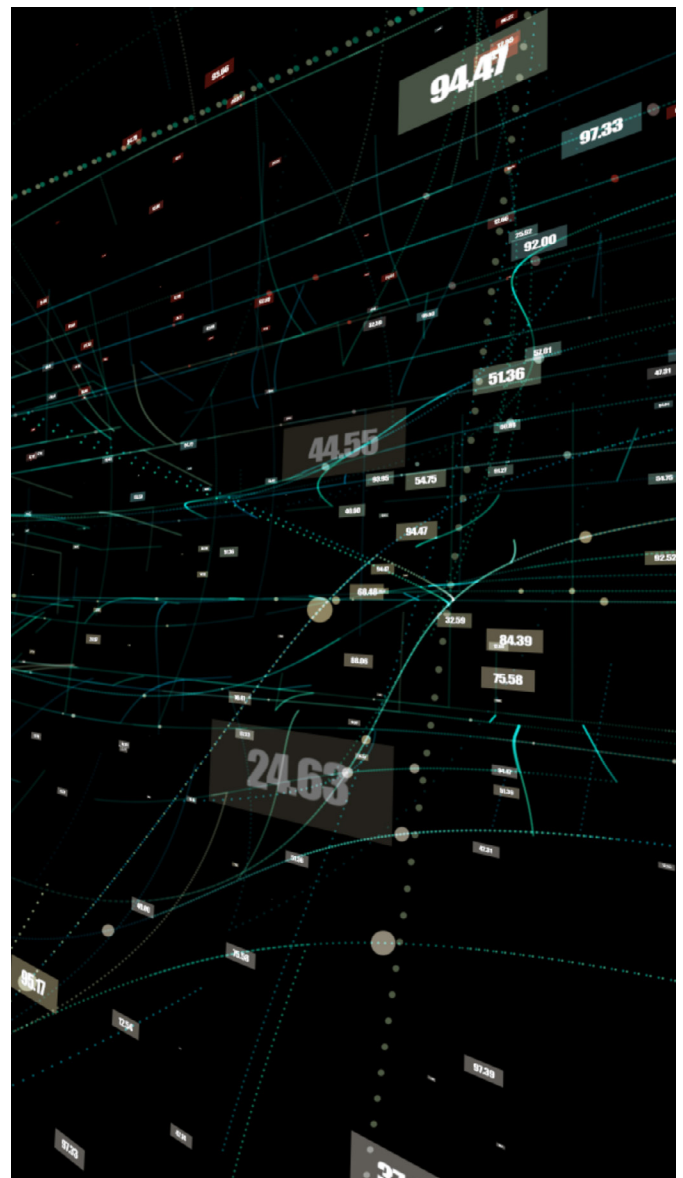
A fundamental distinction exists between CO₂ emissions and non-CO₂ effects, particularly contrails. CO₂, once emitted, can persist in the atmosphere for hundreds to thousands of years, contributing to global warming in a cumulative and long-term manner. In contrast, contrails are short-lived phenomena, typically lasting from minutes to a few hours (on this timescale, considered persistent). However, when persistent, contrails can evolve into cirrus cloud layers that can influence Earth's radiative balance by reflecting incoming sunlight and trapping outgoing longwave radiation, a process known as radiative forcing.

Contrail cirrus clouds can have both warming and cooling climate effects. [3] During the day, they reflect incoming solar radiation which cools the atmosphere (while also trapping outgoing heat radiation from the Earth creating a warming effect). At night, contrails trap outgoing radiation from the Earth, with a net warming effect. There is a scientific consensus that the net effect including day and night is a warming effect.

This warming effect is most pronounced when contrails persist at night or in regions and altitudes with certain atmospheric conditions. Within the category of persistent contrails areas, COMTARs should be identified as a primary target area for significant contrail mitigation actions to be planned and executed by ATM and AUs.

Currently, there are technical limitations to the prediction and identification of ISSRs. An emerging mitigation approach is navigational avoidance, which entails alternate routing of flights to bypass ISSRs. However, this approach can result in environmental trade-offs, such as increased fuel burn and CO₂ emissions, potentially offsetting the intended climate benefits. Furthermore, such rerouting can add complexity to airspace management and reduce available Air Traffic Control (ATC) capacity, especially in high-density regions.

A more targeted strategy focused on persistent contrail mitigation has the ability to balance operational feasibility with environmental impact. Achieving this requires accurate forecasting of persistent contrail formation regions. Forecast improvements would be enabled by the incorporation of additional observational data from on-board sensors, satellite imaging, ground cameras, and/or Light Detection and Ranging (LIDAR) systems. Mitigation efforts should be collaborative, involving ANSPs, Air Traffic Control Officers (ATCOs), airlines, meteorological services, and flight crews. A layered approach from strategic planning to real-time execution is essential for ensuring the operational viability of contrail mitigation.



3. Current State of Contrail Science and ATM Operations

3.1 Factors Influencing Contrail Formation

Understanding the factors that influence the formation of contrails is essential for effective mitigation. Contrail formation is sensitive to both atmospheric conditions and seasonal variations. Coordination with meteorological services plays an important role in identifying contrail-sensitive zones, relevant timeframes and seasons.



Geographic Regions

In Northern/Southern Mid-Latitudes, contrails occur more frequently where ISSRs are more likely to coincide with flight paths. In North Atlantic Tracks (NATs), transatlantic routes between North America and Europe are among the most heavily trafficked and contrail-prone, particularly during colder months. Long-haul flights over polar and mid-latitude regions are also subject to higher contrail formation potential due to atmospheric conditions.² In Tropical Regions, warmer upper-air conditions generally reduce contrail formation, though high-altitude corridors can still occasionally support their development.

Seasonal Patterns

In winter months, lower ambient temperatures at cruising altitudes increase the likelihood of persistent contrails. In summer months, warmer temperatures at altitude reduce the probability of contrail formation. For day-night dynamics, studies show that warming contrails are especially prevalent in winter, due to longer nighttime hours when radiative forcing from cirrus cloud layers is more impactful.

Typical Altitude Range and Size of ISSRs

Persistent contrail formation zones, or ISSRs, where climate-impacting persistent contrails are more likely to form, are typically found between 25,000 and 45,000 feet, which is within the operational altitude range of most commercial aircraft. The probability of persistent contrails increases notably above FL300, where atmospheric conditions for ice crystal formation are more favourable. The typical size of an ISSR is several hundred kilometres in length but less than 1.5 kilometres in height.

² <https://acp.copernicus.org/articles/24/6071/2024/>

3. Current State of Contrail Science and ATM Operations

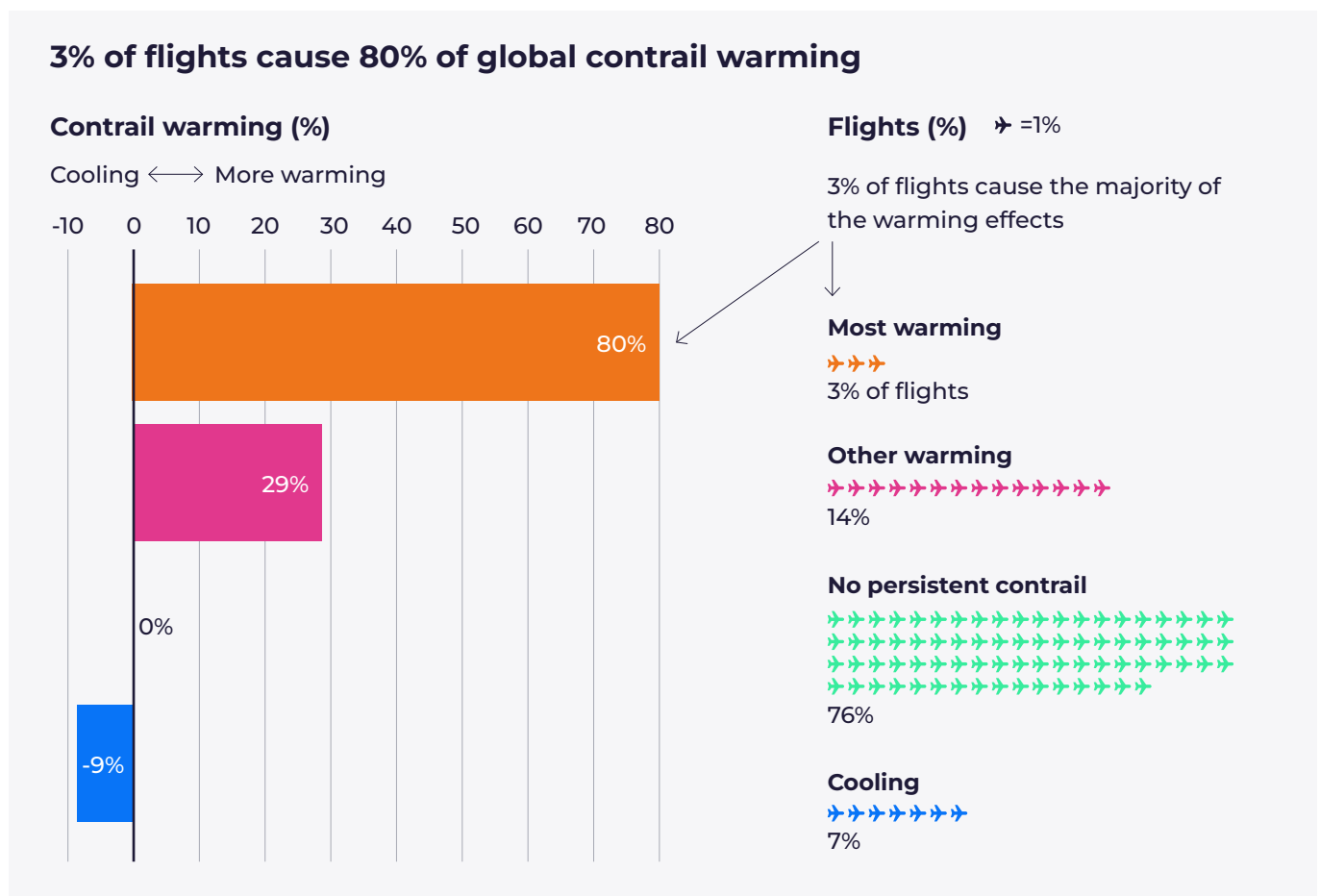
3.2 Contribution of Flights to Contrail Formation

Climate impact from non-CO₂ emissions is not spread evenly across all flights, and certain high-impact flights or high-impact areas of atmosphere can contribute disproportionately to climate impact. Therefore, focusing on a small number of well-chosen flights may lead to a meaningful reduction in overall environmental impact, while limiting the network impacts. A recent study reported that less than three per cent of flights worldwide generated 80 per cent of contrail warming effects in 2019 (in Europe the contribution is from five per cent of flights). See Figure 1 for more details.

While developing a full understanding of all contrails and their impacts is needed, detecting, characterising, and sharing information about high-impact flights and high-impact areas is especially important when it comes to developing mitigation approaches.

This will help ANSPs, supporting the ATCOs' daily management of traffic, find a balance between impacts on operational efficiency while still making an impact on climate mitigation.

Figure 1 – Synopsis of research on flights resulting in contrail impacts



Source: Teoh et al. (2024). Note: Contrail warming has different distributions depending on the region. In Europe, 5% of flights cause 80% of contrail warming in the region.

3. Current State of Contrail Science and ATM Operations

3.3 Climate Metrics and Impact Assessments

The use of appropriate climate metrics is essential for accurately assessing the trade-offs between CO₂ and non-CO₂ effects, such as contrails. Various metrics are used to compare the climate impact of CO₂ and contrails over different time horizons, including:

- Global Warming Potential (GWP)
- Global Temperature-change Potential (GTP)
- Average Temperature Response (ATR)

The selection of a specific metric influences how the benefits of alternate routing are quantified. Short-term metrics like GWP20 emphasise the transient but immediate warming effect of contrails, whereas longer-term metrics such as GWP100 prioritise the enduring impact of CO₂.

For instance, analysis of aviation's climate contribution in 2018 showed that contrails accounted for approximately 55 per cent of the sector's immediate warming effect. This proportion varies by time horizon estimated as GWP:

- 58 per cent for GWP20 (20-year)
- 47 per cent for GWP50 (50-year)
- 36 per cent for GWP100 (100-year)



3.4 Scientific Uncertainty

The science of contrail formation and its climate effects is still evolving. There are still some uncertainties³ and lack of precision, which makes drawing conclusions about the correct mitigation methods and their benefits difficult to accomplish.

The prediction and identification of ISSR's, both their location and timing, is evolving. ISSRs shift with wind and weather patterns, so precisely predicting their location and properties is a technical challenge. More observations in various levels of the atmosphere (particularly of humidity) would be beneficial to give accurate predictions suitable for flight planning and tactical measures.

There are multiple metrics used to assess long-term CO₂ impacts as opposed to short-term contrail impacts. The choice of metric influences the perception of the relative impacts of contrail mitigation. Also, various timeframes are used to assess CO₂ and non-CO₂ impacts which makes the evaluation of trade-offs more difficult.

The mix of varying engines and fuels used by aircraft fleets have an impact on contrail formation. However, the influence of engine technologies and fuels on contrails is not fully understood.⁴

Also, it is hard to predict how ISSRs react to individual flights. These regions will become drier as contrails result in water condensation.⁵ Predicting how an ISSR changes while flights are moving through it (or, avoiding it) is not well understood scientifically. Furthermore, for long-haul flights, ISSRs may change dynamically during the flight resulting in a different contrail mitigation outcome than what was planned pre-flight.

³ <https://www.easa.europa.eu/en/downloads/142614/en>

⁴ [iata-d2-roger-teoh-iata-raes-contrails-workshop-10-11-march-2025.pdf](https://www.iata.org/en/iata-repository/reports-and-statistics/reports-and-publications/iata-raes-contrails-workshop-10-11-march-2025.pdf)

⁵ Estimating the Effective Radiative Forcing of Contrail Cirrus in: Journal of Climate Volume 33 Issue 5 (2020)

4. Current Mitigation Initiatives and Opportunities

Across the academic community and aviation sector, research and real-world initiatives are being conducted to better understand and mitigate contrails. These initiatives include:

1. academic research to improve current models and climate metric understanding;
2. research on engine technologies and alternative fuels and their contrail impact;
3. policy to monitor, report, and verify contrails;
4. early operational trials conducted by airlines, ANSPs, and researchers to avoid persistent contrail formation.

ATM is potentially positioned to support the management of contrail mitigation activities because of its central role in managing flight trajectories and airspace. ATM can support pre-tactical and tactical adjustments to avoid ISSRs while managing traffic flow. The ideal scenario is the ATM system working together in synergy with airlines to mitigate contrail warming.

4.1 Policy Initiatives

Policy initiatives and regulatory frameworks related to contrails are still evolving. One example is the European Commission's (EC) Emissions Trading System (ETS). The EU has an initiative for advancing its climate agenda through enhancements to the Emissions Trading System (ETS). The EU also has an initiative for a Monitoring, Reporting, and Verification (MRV) mechanism designed to quantify non-CO₂ aviation effects, including modelling of contrail formation. MRV is discussed in detail later in this paper. These efforts are part of a broader global movement recognising the role of short-lived climate forcers and aiming to integrate them into regulatory, operational, and technological frameworks.⁶

4.2 Early-Stage Operational Trials

Several airlines have launched pilot programs to test contrail mitigation strategies on a limited scale. [4] [5][6] These efforts primarily explore the feasibility,

operational impact, and effectiveness of mitigation techniques under real-world conditions, though they remain largely limited to airline-centric perspectives, not the wider large-scale air traffic picture. In addition, several ANSPs have conducted validation activities in support of contrail mitigation trials conducted by research organisations.

The main strategy being tested in these trials is aircraft operators adjusting their flight level pre-tactically during flight planning (modifying the filed flight plan before the departure) and/or enroute (directly during the flight phase when they will encounter the contrail area). Lateral deviation is also sometimes considered in airline trails as a mitigation measure, although it is less common.

As such, they are optimising their flight trajectory to include contrail reduction by using current forecasting and prediction capabilities to avoid areas of contrail inducing conditions though pre-flight and tactical phases of flight.

Tactical avoidance by aircraft operators can become a safety issue if not properly coordinated with ATM. Pilots must not deviate from their cleared route without ATC approval except in the case of emergency or for maintaining the safety of the flight operations or the integrity of the aircraft structure.

In such trials, airlines can integrate contrail prediction models into flight planning by utilising advanced weather and atmospheric algorithms to identify potential persistent contrail formation areas. Dynamic flight routing applies real-time data about temperature, humidity, and atmospheric pressure. This can allow for dynamic rerouting during flights to avoid conditions conducive to contrail formation.

ANSPs and ATC systems including flight plan databases should work to accommodate these optimised flight plans submitted by AUs in balance with other operational priorities. This may require updates in the future to flight data processing systems and controller interfaces to ensure clear communication on level changes planned in the flight plan. Depending on the trial, the ATM operation may also need the ability to display information on location of contrail sensitive areas.

⁶ Reducing emissions from aviation - Climate Action - European Commission

4. Current Mitigation Initiatives and Opportunities

4.3 High-Impact Mitigation Opportunities

As mentioned in section three, only some contrails will result in a net warming impact on climate, based on their persistence and other factors, like the time of day. Considering this, reducing their negative climate impact by avoidance may concern only a subset of flights, and there are two frames of reference that emerge:

- **Individually warming contrails** – individual flight contrails where mitigation does not necessarily require coordination.
- **Contrail sensitive area** – a region of likely contrail formation and persistence that would be sufficiently large for multiple flights to pass through it.

Focusing efforts for mitigation on these contrail sensitive areas can target mitigation opportunities around a greater net climate impact and simplify coordination between stakeholders. Focusing on the high impact of COMTARs narrows the focus of operational mitigation to the spatiotemporal subset of flights that would produce climate-warming contrails and could preclude the need to model the climate impact of individual contrails. However, it would require the pairing of accurate meteorological forecasts with flight information. A COMTAR is intended as a region targeted by air traffic management and AUs for significant contrail mitigation actions to be planned and executed.

4.4 Effects of Engine Design and Fuel Composition

Aviation decarbonisation efforts via technology will require large investments and long timeframes to implement, whereas contrail mitigation may be possible at relatively lower costs in the near-to mid-term.

Engine technology affects contrail formation via exhaust temperature and particulate emissions. Next-generation aircraft engines may produce less particulate matter (PM), which is the nucleus around which ice crystals form and create contrails. New engine technology to reduce engine emissions is a critical component of the broader goal of reducing aviation's climate impacts but has a much longer time horizon than operational mitigation.

The introduction of jet engine fuels that produce fewer particles and have lower sulphur content (Sustainable Aviation Fuel [SAF] and other alternative fuel compositions) may impact the formation and persistence of contrails. Fuels made from biomass, algae, or synthetic sources produce fewer "ice nuclei" compared to conventional jet fuel, potentially reducing contrail climate impact. But the development and deployment of new fuels into the system will require long timeframes.

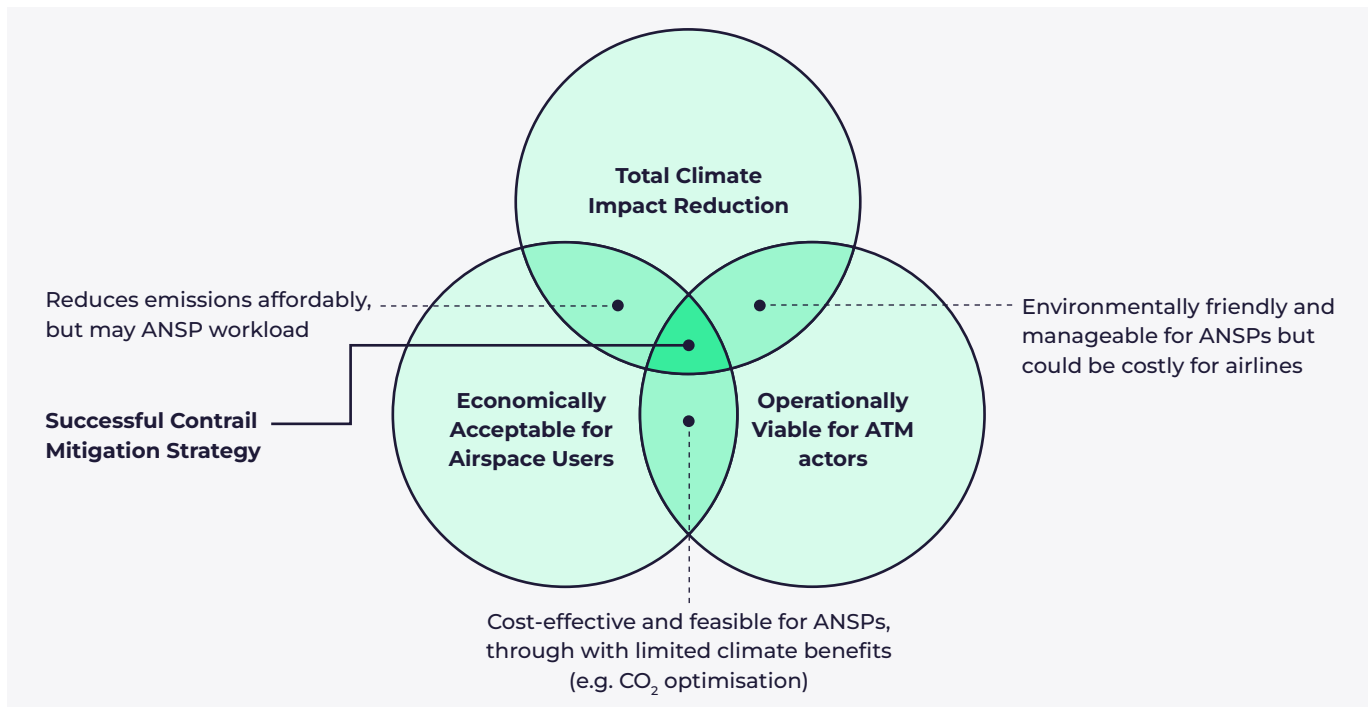


5. Future Contrail Mitigation Role for ATM

Successful contrail mitigation requires a balance between climate impact reduction (for both CO₂ and non-CO₂ impacts), economic implications, and operational viability.

To ensure contrail reduction and associated reduction in climate warming effect, alignment must be achieved through a collaborative approach among all stakeholders. The three main drivers are described next, and presented in Figure 3, followed by an overview of involved stakeholders.

Figure 3 – Contrail Mitigation Strategy



Contrail mitigation strategy is built on three essential pillars:

- 1. Climate Impact Reduction:** Efforts to mitigate contrail impacts through operational changes must ensure that any trade-offs (e.g., potential additional CO₂ emissions from alternate routing) do not outweigh the benefits of the contrail mitigation in terms of overall climate impact. Focusing mitigation strategies on COMTARs can support this pillar.
- 2. Economic Acceptability for ANSPs and AUs:** For mitigation efforts to be practical and widely adopted, they must be economically viable for ANSPs, airlines, and other Airspace Users. For airlines, this requires balancing environmental adjustments with fuel efficiency and other operational costs to ensure that the benefits are sustainable. For ANSPs, potential costs are related to controller training and implementing decision support tools.

- 3. Operational Viability for Airspace Stakeholders:** Each mitigation phase should be carefully aligned with ATM operations, to ensure seamless integration with environmental priorities. This alignment must preserve ATC capacity, appropriately manage the workload of both ATCOs and AUs and consider the complexity of airspace and operations. Above all, safety must remain uncompromised throughout every stage of implementation.

Much will depend on the regulatory frameworks developed and implemented to either mandate or incentivise action to address non-CO₂ effects, while ensuring that both AUs and ANSPs are able to participate in mitigation efforts in a manner that is operationally feasible and economically sustainable.

This chapter outlines how Airspace Stakeholders and ANSPs can collaborate and align on contrail mitigation.

5. Future Contrail Mitigation Role for ATM

5.1 Collaboration and Roles

Mitigating the climate impact of contrails is not the responsibility of a single entity. It requires a coordinated, multi-stakeholder approach that spans strategic planning, real-time operations, and post-operational assessment.

Effective mitigation depends on the seamless integration of roles across the aviation ecosystem, supported by ATM as a unifying enabler of network-wide action. The following sections describe the relevant stakeholder groups and their roles in contrail mitigation.

Air Navigation Service Providers (ANSPs)

ANSPs are central to contrail mitigation efforts, managing airspace capacity and flow while facilitating tactical or strategic altitude adjustments that help aircraft avoid ISSRs. Their situational awareness, traffic coordination, and integration of meteorological data are critical to implementing mitigation strategies safely and efficiently.

Air Traffic Flow Management (ATFM) functions (for example, European Network Manager, US FAA Command Centre, Canadian National Operation Centre, etc.) enable broader coordination across multiple Flight Information Regions (FIRs), managing traffic at the regional and network level. Their role is especially vital in supporting cross-border mitigation scenarios, where Collaborative Decision-Making (CDM) is essential for system-wide efficiency and environmental benefit.

Airspace Users (AUs)

Airlines and flight operators play a direct role in contrail mitigation by filing optimised flight plans and executing in-flight adjustments where feasible. Their decisions in the pre-tactical and tactical phases, can influence whether a flight contributes to or avoids contrail formation.

Meteorological Data Providers

Accurate contrail mitigation relies on accurate forecasting and robust, real-time atmospheric data. In particular temperature and relative humidity are necessary for forecasting contrail formation and persistence.

Meteorological service providers forecast ISSRs and other contrail-prone conditions, informing both ANSP and AU decisions. Additionally, real-time measurement supports tactical measures and post-validation of the effectiveness of mitigation measures with respect to climate impact.

Advances in modelling atmospheric science and weather prediction should significantly enhance contrail mitigation.

Software developers and data providers

The providers of data (such as the meteorological data providers) and the organisations that can combine such data and compute high contrail risk areas or validate contrail formation post-flight also play an important role in mitigating contrails. These organisations have slightly different approaches, but all provide contrail mitigation information. This information can be used by AUs or researchers to predict or validate contrail formation but can also be used to inform flyers on their contrail impact. These stakeholders often play a role in research projects but also have public facing Application Programming Interfaces (APIs) or platforms.

In addition, Computerised Flight-Planning Service Providers (CFSPs) can implement a weighting or cost function for contrails and subsequently recommend a flight plan that takes contrails into account. Several tools have been developed or are in development by flight planners that allow contrail avoidance to be integrated into flight planning processes. However, meteorological data (source and timestamp), models used, and cost functions may differ per AU and flight planning system, which may lead to different outcomes.

Researchers

Contrail modelling, validation, and mitigation continues to develop at an academic level. Researchers from institutes globally do research to improve the current models, better understand the metrics, and test new opportunities and data to validate contrails. Their role is critical to ensure that the uncertainties reduce and that contrail mitigation is operationally effective.

5. Future Contrail Mitigation Role for ATM

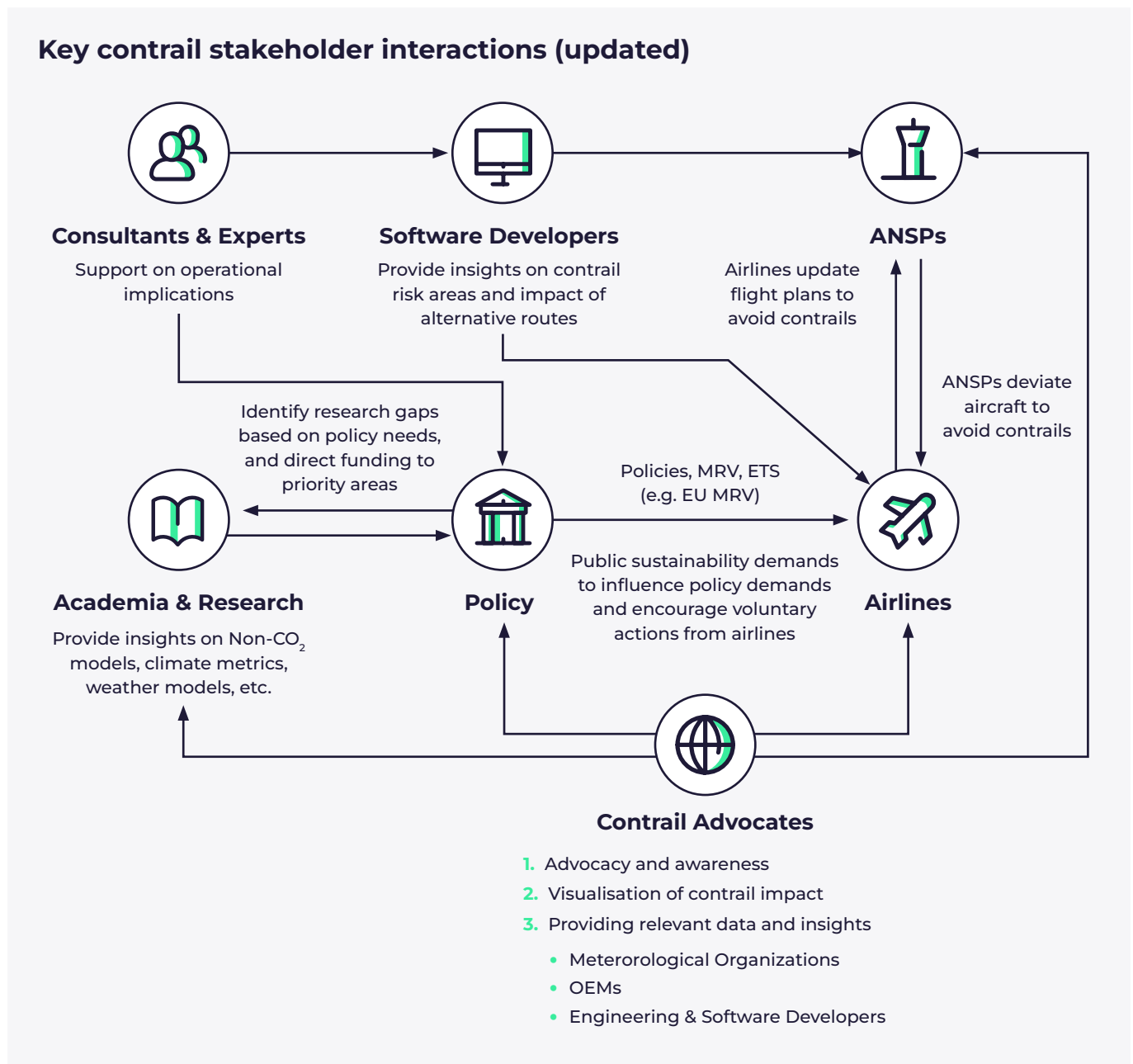
Regulators and Policy Bodies

Regulatory frameworks provide the foundation for harmonised action.

As an example, the European Commission is developing MRV mechanisms and exploring future guidance to account for non-CO₂ effects, including contrails.

Figure 4 depicts the stakeholder interactions for contrail mitigation. The collaboration and roles of the stakeholders listed above are included, as well as other involved parties (academia, industry experts, software developers, and advocates).

Figure 4 – Contrail stakeholder interactions (Source: To70)



5. Future Contrail Mitigation Role for ATM

5.2 ATM Considerations

Many contrail mitigation efforts have focused on airline-led flight planning and operational trials. While valuable, they lack scalability and system-wide coordination. Contrail mitigation should be framed as a shared challenge in which ATM plays a central, enabling role. Therefore, this white paper aims to propose potential strategies in a collaborative approach that includes the role of the ANSP.

ATM is a uniquely positioned actor for managing mitigation strategies at scale. ATM's coordination function allows it to:

- Monitor and manage traffic flows across congested regions and airspace sectors;
- Facilitate altitude and trajectory adjustments both tactically and pre-tactically while accounting for operational complexity;
- Coordinate mitigation strategies across multiple AUs, reducing unintended effects such as overloading neighbouring sectors.

Without ATM's network-wide oversight, individual airline interventions, though well-intentioned, can lead to increased complexity, reduced predictability, and even higher emissions through inefficient routing.

The sections below present the considerations and challenges to contrail mitigation for ANSPs.

Trajectory Optimisation Through ATM-AU Synergy

Contrail mitigation efforts would benefit from airlines and ANSPs working together. Airlines can identify flights with high mitigation potential, while ANSPs coordinate adjustments system-wide to avoid sector overloads and manage network impacts. ATM's ability to balance contrail mitigation with sector capacity and traffic complexity is critical. Vertical flight level changes may be less complex and potentially disruptive than lateral alternate routing but still require pre-tactical deconfliction.

Lessons from Weather Avoidance

Contrail-sensitive zones can be managed similarly to convective weather avoidance, designating ISSR areas for consideration of alternate routing. Weather conditions are a major driver of complexity in ATM, impacting safety, capacity, and system efficiency. A modern and resilient ATM must be integrated with advanced weather systems to operate safely, efficiently, and sustainably.

When an aircraft encounters adverse weather conditions, a series of operational, management, and safety procedures are activated, involving both the flight crew and ATC. These existing weather avoidance procedures have the potential to inform contrail mitigation procedures. ATCOs may not always have perfect visibility into real-time climate impacts, but enabling mitigation protocols within ATM systems can guide effective responses.

As meteorological services and contrail forecasting methods improve, equipping ATCOs and AUs with contrail-aware decision support tools can help to enable the integration of contrail mitigation strategies into regular operations. However, it is important to note that while severe weather avoidance is an inherent safety requirement, contrail mitigation would only be pursued when feasible (that is, when all safety and operational needs have been met).



5. Future Contrail Mitigation Role for ATM

Policy and System-Level Integration

Global policy frameworks are beginning to acknowledge the importance of non-CO₂ effects. For example, the European Union's MRV mechanism, introduced under the ETS, mandates that operators begin tracking non-CO₂ effects—including modeling estimates of contrails—started in 2025, with expanded obligations by 2027. In 2025 and 2026, reporting is mandatory only for routes within the European Economic Area (EEA). From 2027 onwards, the MRV will extend to include all flights departing from or arriving to the EEA.

As the European Commission develops the MRV system, the choice of metric will play a vital role in how mitigation outcomes are assessed and incentivised. While regulations for contrail mitigation are not yet in place, these data-driven frameworks will inform future standards. The data collected during this period can potentially support studies to analyse potential methods and measures to reduce these non-CO₂ emissions. This can also be an opportunity for ANSPs to engage with operators and define the role of ATM in developing coordinated solutions.

The climate impact of contrails cannot be addressed effectively through isolated airline efforts alone. By aligning tactical ATM capabilities with airline agility and regulatory vision, the aviation industry may be able to deploy contrail mitigation at scale, maximising environmental benefit while preserving operational integrity.

Collaborative Research and Global Standards

Encouraging international collaboration on research and the development of new guidance or standards for contrail management will help accelerate the adoption of mitigation technologies. Global coordination can lead to more efficient airspace management in the future.

Improving Scientific Understanding and Utilising Data

Continued research on the physics of contrail formation will enable better mitigation strategies. Sustained investment in atmospheric research and partnerships with environmental agencies could provide the data needed for more effective approaches. Artificial Intelligence (AI) models and Machine Learning (ML) are being developed to predict where and when contrails will form based on atmospheric data and historical flight data.

Machine learning can be used to fine-tune flight routes and altitudes to minimise the occurrence of contrails. Airlines may choose to use AI-driven optimisation algorithms to balance fuel efficiency with contrail reduction, leading to smarter flight planning decisions.

With more data from weather satellites and AI-powered modelling (algorithms), AUs can adjust their flight routing/profile in real time to minimise contrail creation. This has the potential to be managed autonomously and facilitated by newly developed tools for airspace stakeholders.

Trajectory Based Operations

Trajectory Based Operations (TBO) is an operational concept in ATM that aims to enhance the efficiency, predictability, and safety of air traffic by managing flights based on their 4D trajectories (latitude, longitude, altitude, and time).

At its core, TBO is about managing flights based on their intended path through space and time, rather than relying solely on fixed airways or reactive control. It enables collaborative decision-making between airspace users (like airlines), ANSPs, and other stakeholders.

An important feature of TBO is dynamic replanning. Trajectories can be adjusted in real-time to respond to changing conditions (e.g., weather, congestion). It therefore has the potential to be an enabler for contrail mitigation.

TBO is a key component of airspace modernisation programmes, such as NextGen (USA) and SESAR (Europe). It is also being adopted in regions like Asia-Pacific (APAC) under ICAO's Global Air Navigation Plan (GANP). Its implementation is scheduled for 2030-2045 for its three phases.

5. Future Contrail Mitigation Role for ATM

5.3 ATM's Role in a Hybrid Contrail Mitigation Approach

To ensure effective and scalable contrail mitigation, a hybrid approach is proposed that leverages the strengths of both airline-based and ATM-based strategies through CDM. Such a model would allow for real-time adaptability, network-wide efficiency, and targeted action aligning environmental, operational, and safety priorities. ANSPs would take a leading role in the strategic and/or pre-tactical planning effort in advance then collaborate with all stakeholders on the day of operation.

Aircraft operators acting independently, especially in busy or high-density airspace, can increase complexity for ATC and may limit the overall effectiveness of mitigation. Likewise, while ANSPs can implement airspace-wide strategies, these are most effective when coordinated with airline actions. Without such coordination, there is a risk of overloading adjacent ATC sectors or reducing flight efficiency. A more effective outcome may be achieved when both parties align their respective approaches to support contrail mitigation collaboratively.

This section outlines how ANSPs can collaborate with Airspace Stakeholders and align on contrail mitigation approaches by drawing on their current operational roles.

When both work together, mitigation efforts in COMTARs can be more effectively scaled. The hybrid approach allows for:

- Shared identification of COMTARs as areas of focus;
- Pre-tactical and tactical coordination of traffic around these regions;
- Coordination and alignment on data and models used to assess COMTAR regions;
- Coordination and alignment on defining the balance between environmental goals, both CO₂ and non-CO₂, as well as operational constraints such as ATC capacity.

Contrail mitigation within ATM is a continuous process, involving multiple phases of flight management: the strategic phase, pre-tactical phase, execution phase, and post-operational phase. Each phase brings unique implications and requires the involvement of specific actors to ensure effective coordination.



5. Future Contrail Mitigation Role for ATM

Strategic Phase

In the strategic phase, the focus is on identifying long-term trends based on historical traffic and climate data, allowing stakeholders to assess the potential impact of contrail mitigation on air operations, even if recurrent or usual positioning of ISSR is not the single factor to consider for planning (for example: season, winter versus summer, and time of day – day versus night). This approach helps airspace stakeholders understand recurring ISSR patterns and develop baseline strategies that anticipate future contrail mitigation needs, building on mitigation patterns that have worked without causing significant overload or that have been operationally accepted by various ATM stakeholders.

Key performance criteria:

- **Trend Detection:** Analysing historical data on traffic patterns and climate conditions to identify trends in contrail formation, providing insight into approximately where and when ISSRs are likely to affect airspace operations.
- **Impact Assessment:** Evaluating the potential operational impacts of contrail mitigation strategies on airspace capacity, efficiency, and safety to guide future planning.
- **Data Integration with Post-Operational Phase:** Leveraging insights from post-operational analyses to refine and validate strategic decisions, supporting the continuous improvement and adaptation of mitigation strategies over time.
- **Information Continuity:** Ensuring seamless information flows from the strategic to the pre-tactical phase to avoid any disjointed transitions, enabling smoother adjustments and alignment between long-term planning and immediate operational needs.

Pre-Tactical Phase

In this planning stage, ANSPs, primarily through the Flow Management Position (FMP), the Network Manager (where applicable), and airlines need reliable access to information on where ISSRs are expected to form, including data on the potential impact of flights passing through these zones, as well as the anticipated geographical and temporal evolution of the ISSR. Based on all these data points, the objective is to identify COMTARs where mitigation would significantly reduce the overall climate impact.

This information should then be used to generate alternative flight plans along the contrail impacted area that minimise climate effects and are operationally viable.

Since Airspace Stakeholders/CFSPs alone may not have full visibility on the feasibility of new flight plans or their impact on traffic, this process needs to be iterative between ANSPs and AUs consistently identify the best candidate flights for optimisation. As feedback from ANSPs is essential to confirm whether a COMTAR is indeed optimisable within ATM constraints, the process must be ongoing and responsive.

It requires a high degree of automation to efficiently manage the iterative exchanges between all the stakeholders and ensure that each AU has access to the latest and most feasible flight plan based on evolving ISSR conditions and contrail mitigation potential. Moreover, the use of different data sources or even different timestamps of the same data source may lead to different insights between an ANSP and AU. Clear processes on how to deal with these changes should be in place.

Key performance criteria:

- **ISSR Prediction Quality:** The ability to forecast ISSR locations well in advance, with high accuracy and minimal uncertainty.
- **Real-Time Updates:** The capacity to continuously access the latest and most accurate ISSR predictions, provided by external sources, ensuring that all stakeholders work with the best available data rather than calculating zones themselves.
- **Information Sharing:** Ensuring that ISSR predictions & associated impacts are effectively distributed and accessible to all stakeholders, supported by a Single Source of Truth (SSoT) to centralise and standardise data.

5. Future Contrail Mitigation Role for ATM

Execution Phase

The main objective in this phase is to limit tactical adjustments for operational contrail mitigation as much as possible, keeping flight routing modifications minimal. However, some situations may necessitate real-time adjustments such as trajectory management. In these cases, communication between ANSPs and AUs is essential to support dynamic and collaborative decision-making.

Key performance criteria:

- **Real-Time Communication:** Ensuring seamless, live communication between ATCOs, FMPs, and dispatchers to enable swift adjustments to flight trajectory in response to changing ISSR conditions.
- **Cross-Border Coordination:** Facilitating effective cross-border collaboration to share ISSR updates and other contrail data, supporting continuous mitigation efforts across airspace boundaries.
- **Adaptability to ISSR Updates:** Ability to incorporate real-time updates on ISSR locations, enabling dynamic path adjustments to avoid persistent warming contrail formation while maintaining safe operations.

Post-Operational Phase

In this phase, the focus is on evaluating and quantifying the effectiveness of contrail mitigation strategies after flights have been completed. This involves a thorough analysis of flight data to assess the success of mitigation efforts, both in terms of environmental impact and operational efficiency.

One critical aspect of this phase is the integration of advanced verification tools currently under development or being deployed. Technologies such as satellite imagery, ground-based cameras, and humidity sensors will play a crucial role in validating contrail formation and assessing ISSR conditions.

These verification methods enable more precise measurement of actual contrail formation, helping to confirm whether mitigation actions were effective or if adjustments are needed.

Key performance criteria:

- **Data Storage and Knowledge Management:** Efficiently storing and managing contrails-related data, including flight trajectories, ISSR conditions, and mitigation actions, to build a comprehensive knowledge base for ongoing improvements.
- **Metadata Collection and Analysis:** Collecting detailed metadata on each mitigation attempt to evaluate patterns, outcomes, and impacts on traffic flow, allowing for refinement of strategies in both tactical and strategic planning.
- **Integration of Verification Tools:** Leveraging new verification capabilities, such as satellite imagery, ground sensors, and humidity measurements, to enhance the accuracy of post-flight analysis and improve real-time responsiveness in other phases.

By establishing a robust feedback loop from the post-operational phase, insights from verification tools and data analysis will serve as a foundation for future strategic and pre-tactical planning.

Contrail mitigation is a continuous process that spans multiple phases, from strategic planning to post-operational analysis. For any strategy to be successful, it requires the active involvement of both AUs and ATC, ensuring that trajectory optimisations are coordinated effectively across all phases.



5. Future Contrail Mitigation Role for ATM

Implementation Considerations

A hybrid approach to contrail mitigation ensures that contrail mitigation actions do not create unintended consequences elsewhere in the system, and that actions taken by aircraft operators and ANSPs do not contradict each other. A hybrid contrail mitigation model rooted in collaboration offers a path forward for operational feasibility, environmental impact, and system sustainability. By pairing airlines' flexibility and economic insight with ATM's network-level oversight and safety mandate, this approach can ensure coordinated, efficient, and adaptive responses to the growing need for climate-conscious air traffic management. The implementation of the hybrid approach is further described in Table 1. Exactly how this collaborative effort plays out will vary by region, depending on ANSP capabilities, existing roles, responsibilities, and working relationships between the ANSP, airlines and a network manager (if applicable).

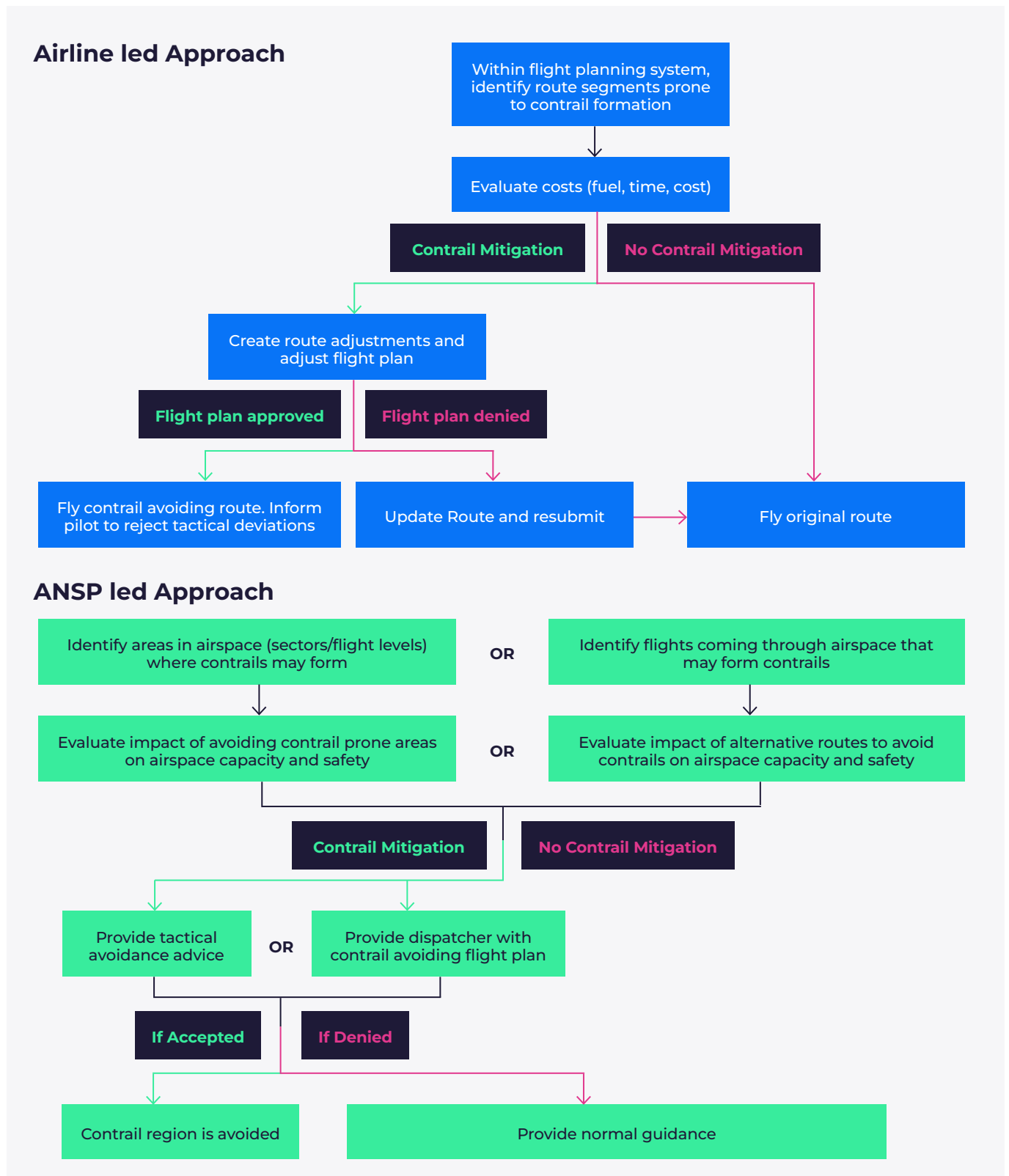
Table 1 – Implementation Considerations for the Hybrid Approach

Aspect	Hybrid Approach
Scope & Coordination	Combines individual airline flexibility with network-level ATM coordination. Airlines optimise their trajectories within a shared framework guided by centralised constraints and opportunities. Shared situational awareness tools and strategic ISSR overlays enable coordinated planning and response.
Impact on ATC Complexity	ATM provides structured parameters for contrail mitigation (e.g., prioritised ISSR zones, altitude bands as suggested avoidance zones), while AUs adapt flight plans within those parameters. CDM ensures that the aggregation of airline strategies does not overwhelm sectors or shift complexity unsustainably.
Scalability	Scalable for different airspace density. Network-level coordination enables wider coverage, while airlines execute flight-specific adjustments. This dual approach ensures adaptability and resilience.
Efficacy	Prioritise high-impact flights (e.g., long-hauls in high-density ISSRs) using shared climate impact metrics. Enables cumulative environmental benefits while minimising inefficiencies. Coordinated use of flexible airspace, dynamic trajectory planning, and altitude management supports measurable outcomes.
Real-Time Feasibility	Strategic and pre-tactical planning led by airlines and network managers, with tactical execution supported by ATM. Real-time feasibility improves via common situational awareness, digital tools (e.g., SWIM), and automation of advisories for contrail-sensitive regions.
Economic Feasibility & Trade-off Metrics	Airlines evaluate flight-specific cost-benefit scenarios, while ATM assesses capacity, safety, and overall system impact. Joint planning frameworks include environmental prioritisation where appropriate. A common dashboard or interface can support transparency and informed decision-making. Metrics are defined to make tradeoff decisions (for example: CO ₂ emissions versus non-CO ₂ emissions).
Weather and ISSR Data	Integration with meteorological data providers and more reliable forecasts of ISSRs enable better decision making. Coordination across different regions and reporting of observations in real time enabled by advanced tools and research.

5. Future Contrail Mitigation Role for ATM

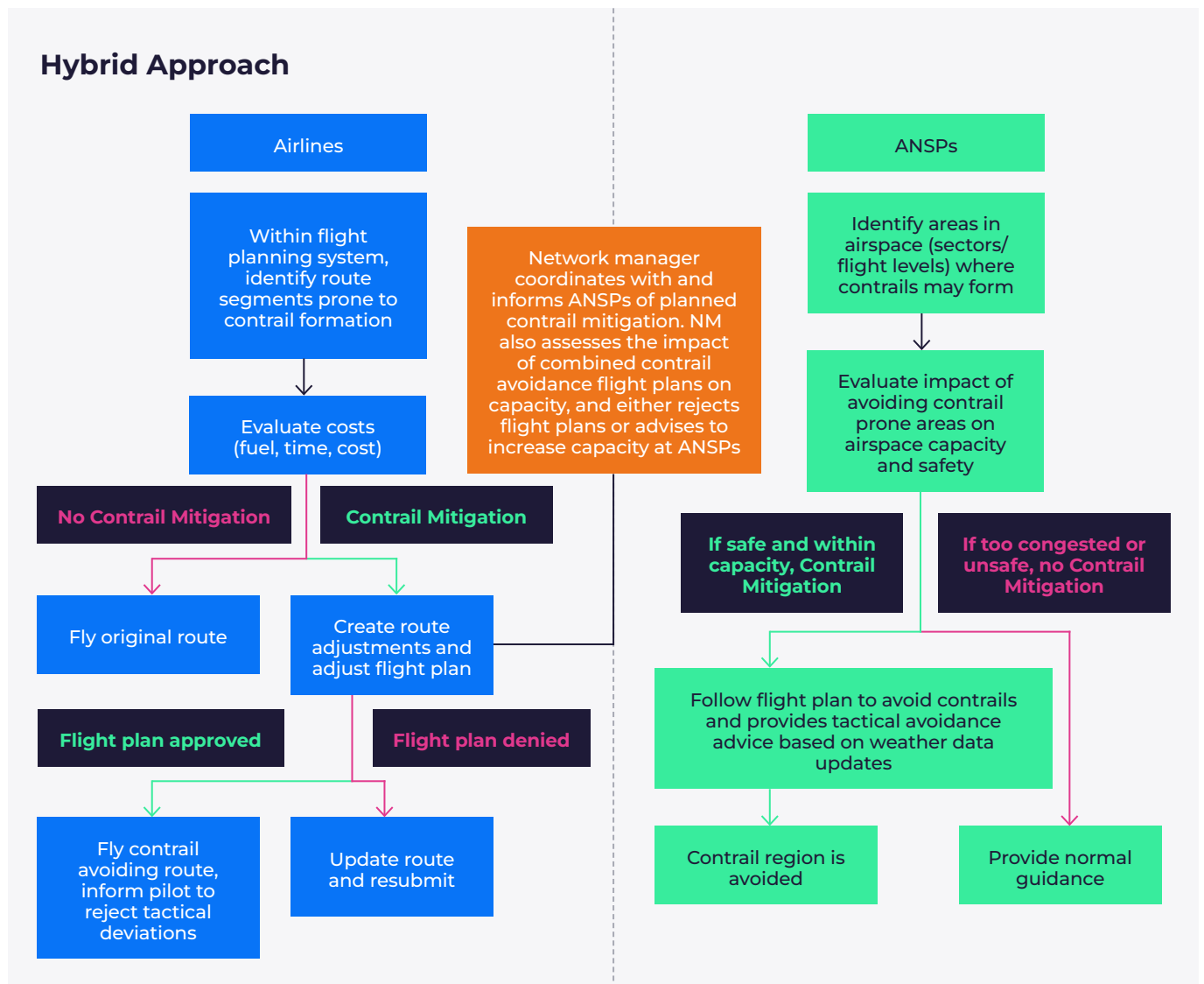
Finally, a flowchart showing a notional airline approach, a notional ANSP approach and a notional I hybrid contrail mitigation approach is shown in the figures below.

Figure 2 – Potential contrail mitigation approaches



5. Future Contrail Mitigation Role for ATM

Figure 2 – Potential contrail mitigation approaches



6. Challenges

As contrail mitigation becomes an increasingly important component of aviation's broader climate strategy, a range of challenges - technical, operational, and regulatory - must be addressed to move from concept to implementation. These challenges are complex, interrelated, and demand-coordinated action across the aviation ecosystem.

6.1 Technical Challenges

One of the most significant hurdles in mitigating contrail-induced climate effects is the limited ability to accurately predict, detect, and quantify contrail formation in advance and in real time.

While scientific progress has been made in understanding contrail dynamics, forecasting the exact location, timing, and impact of contrail formation remains difficult due to gaps in high-resolution atmospheric humidity data and model validation. Improved prediction capabilities are essential, as only a fraction of contrails contribute significantly to warming –primarily those that evolve into persistent cirrus clouds in ISSRs, which tend to occur disproportionately in specific regions such as the North Atlantic, Europe, and the mid-latitudes.

Efforts to refine contrail impact estimation are further complicated by the variability of atmospheric conditions and the short-lived but non-linear climate forcing effects of contrails. Although satellite and ground-based monitoring technologies exist, their global coverage and real-time utility are still limited. There is a growing need for advanced data systems and observational tools capable of tracking persistent contrails on individual flights and informing actionable decision-making.

Ongoing innovations in aircraft engine design, fuel efficiency, and alternative propulsion systems including Sustainable Aviation Fuels (SAF), electric, and hydrogen technologies show potential to reduce emissions of particulates and/or water vapor, which are precursors to contrail formation. However, these advancements are still years from widespread deployment. Even with full SAF usage, contrail formation will not be entirely eliminated, reinforcing a multifaceted mitigation strategy.

Further research is needed to assess the tradeoff between contrail mitigation and increased CO₂ emissions. These are measured in disparate units that must be translated into long-term climate effects.

Importantly, continuous validation of contrail models against real-world flight data and flight trials is crucial to improving the reliability of mitigation strategies. Such trials can help determine which operational changes meaningfully reduce contrail formation without unintended consequences.

6.2 Operational Challenges

Operationalising contrail mitigation at scale introduces trade-offs that must be carefully managed. One commonly proposed approach involves modifying flight trajectories either vertically or laterally to avoid regions where persistent contrails are likely to form. While these adjustments are technically feasible and often fall under the discretion of the AUs, their successful implementation depends heavily on coordination with ANSPs, especially in capacity-constrained or complex airspace.

Routing flights to avoid ISSRs may result in longer trajectories, increased fuel consumption, or disruption to airline schedules (including changing the time of arrival to the destination airport). In many cases, vertical profile adjustments offer a more efficient compromise by avoiding contrail-forming altitudes while maintaining lateral routing. However, applying these strategies in busy airspace such as Europe or the North Atlantic can strain ATC capacity, increase controller workload, and lead to unpredictable traffic patterns.

The feasibility of tactical contrail mitigation also hinges on system-wide coordination that goes beyond pre-tactical planning. Real-time awareness of atmospheric conditions and dynamic flight adjustments on the day of operation are equally important to ensure mitigation is effective without degrading safety or efficiency. This requires integration of contrail prediction tools into air traffic systems and collaborative decision-making between AUs and ANSPs.

While many advanced mitigation technologies are in development, their readiness levels vary. Concepts such as dynamic cruise level optimisation and ATM-integrated environmental decision tools are progressing but need further maturation to be leveraged in the near term, assuming contrail forecasting and prediction capabilities also improve.

6. Challenges

6.3 Regulatory Challenges

Contrail mitigation efforts are currently constrained by the absence of a harmonised global regulatory framework. Initiatives such as the EU ETS are introducing mechanisms like MRV for non-CO₂ effects, these start regionally but will expand to all in and outbound flights to EU airports from 2027. However, the results of the MRV are currently only modeling estimated contrails, and do not support incentives for contrail avoidance. As of now, there are no (global) mandates or incentives for contrail mitigation, and efforts are largely voluntary through trials, or research based.

International cooperation will be essential to align regional efforts and create standardised methodologies for assessing and reporting contrail-related climate impacts. Organisations such as ICAO and CANSO are well-positioned to facilitate this dialogue and develop guidance that accounts for both environmental ambition and operational feasibility.

Effective contrail mitigation also requires sustained collaboration and a legal framework among diverse stakeholders—regulators, ANSPs, AUs, manufacturers, researchers, and climate experts. However, balancing diverse priorities remains a challenge. Airlines may prioritise cost and schedule adherence, while regulators focus on emissions targets. Governments must weigh climate action against economic and political considerations.

Environmental trade-offs also require careful evaluation. While routing to avoid contrails may reduce short-term radiative forcing, it can result in increased CO₂ emissions or disrupt efficient traffic flows. These system-level impacts must be understood holistically, not only during planning phases but also through real-time operational performance monitoring.

A final challenge lies in the lack of dedicated financial mechanisms that incentivise contrail mitigation. Although carbon markets and emissions trading schemes create some economic drivers for overall CO₂ reduction, they currently do not account for the unique climate effects of contrails. While care must be taken not to imply contrail mitigation can be traded for CO₂ reductions, integrated climate accounting that includes both is essential. Mitigation of contrails must complement—not replace—efforts to reduce long-lived CO₂ emissions. However, implementing such measures at a scale will necessitate close collaboration among governments, airlines, ANSPs, and researchers. Regulatory frameworks are still evolving and have yet to fully align with the goal of contrail mitigation. Prioritising this issue alongside broader sustainability objectives is essential.

Innovative technologies and smarter operational strategies can help aviation achieve a better balance between efficiency and environmental responsibility. The path forward lies in fostering coordinated action, informed trade-offs, and a shared commitment to climate-conscious air traffic management.



6. Challenges

6.4 Implementation Challenges

Implementing contrail mitigation strategies at scale presents numerous challenges:

- **Scalability and Systemic Impacts:** Large-scale implementation can introduce unintended side effects on traffic flows and system performance, particularly in complex, high-density airspace.
- **High-Density Airspace Adaptation:** While trials may begin in less congested regions or times of day, expanding to core traffic corridors like Northern Europe will present significant operational hurdles.
- **System-Agnostic Integration:** Any proposed solution must be compatible with diverse ATM systems and procedures to ensure broad adoption.
- **Personnel Training:** ATCOs, FMPs, and supervisory staff will require targeted training to handle increased workload and decision-making complexity.
- **Forecasting Uncertainty:** Limitations in accurately predicting ISSRs remain a major obstacle. While ATM cannot directly improve forecast precision, these uncertainties must be factored into operational planning and future system design.
- **Incentivisation and Equity:** While airlines may realise tangible benefits from contrail mitigation (e.g., through EU ETS adjustments), ANSPs often face increased workload without corresponding incentives. Regulatory frameworks should recognise ANSP contributions to environmental objectives.
- **Operational Workload and Communication:** Greater coordination with airline dispatchers and increased plan revisions may burden both ANSPs and operators. Efficient communication protocols will be essential to manage this impact.
- **Alignment Between Systems:** Flight planning systems, ATM led contrail mitigation systems and even post operational contrail validation systems will likely use different models and data, both due to data availability and operational feasibility. The differences must in any case be understood and ideally should be more closely aligned to ensure that actions being taken by all stakeholders are mutually beneficial and not conflicting.



7. Conclusion

Contrail mitigation has garnered significant attention due to the potential impact of contrails on climate change. The feasibility of operational contrail mitigation is promising, but requires a multifaceted approach involving collaboration, technology, research, operational changes, and strong policy support.

Collaboration among all stakeholders involved (e.g., AUs, regulators, ANSPs, researchers, data providers, OEMs, etc.) is essential to design and implement mitigation strategies. Each stakeholder plays a key role towards improving the scientific foundation, advancing predictive capabilities, and potentially developing operational tools and harmonised procedures that incorporate contrail mitigation considerations alongside safety and efficiency.

Continued research and investment are crucial for advancing contrail mitigation efforts. More simulations and trials that integrate the proposed hybrid approach presented in Section 5.3 are required to fully understand the roles each stakeholder will have, and the operational impact of a hybrid approach must be assessed for both ANSPs and AUs. With these insights, contrail mitigation, and specifically the role of ATM, can be aligned and improved.

While challenges remain, the potential environmental benefits make contrail mitigation a worthwhile endeavour. As the regulatory framework evolves and scientific understanding improves, ANSPs must continue to be informed and involved in aviation activities in this area.

Recommendations

Based on the challenges described above, alongside the opportunities for increased ANSP involvement, the following recommendations ensure that operational considerations are accounted for and that ANSPs are sufficiently engaged in the process.

- **Execute additional trials with defined roles for ANSPs and Network Managers.** This would strengthen ANSP understanding of contrail mitigation operations, while clarifying data-sharing frameworks, procedures, resource implications, and operational impacts on staff. Insights gained from these trials and related developments should be systematically captured to further advance the scientific understanding of contrails.
- **Ensure ANSPs are part of the conversation in policy development.** Only if ANSPs are involved can their role be fully considered. This is critical to avoid contrail mitigation approaches that ignore the critical role of airspace safety and capacity.
- **Consider how contrail management strategies could be integrated into ATM systems.** Whether in network management, flow management, or individual ATC procedures and processes, it is important to consider the ways in which ATM systems could potentially enable (or constrain) contrail mitigation strategies.
- **Assess the impact of contrail mitigation strategies on ATM.** As contrail mitigation strategies are developed and tested, these strategies must be monitored and assessed to understand the impact on ATM including capacity, workload, and safety.

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